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Radio Variability of Sgr A* at Centimeter Wavelengths

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Abstract. Results of two years of continuous monitoring of flux density variations at 8.3 and 2.3 GHz of the Galactic Center super-massive black hole candidate Sgr A* are reported. The average RMS modulation indices are 6% and 2.5% at 8.3 & 2.3 GHz respectively. There is a certain degree of correlation between both frequencies. The timescale of variability at 8.3 & 2.3 GHz is between 50 and 200 days. We cannot confirm a λ^2 dependence of the timescale. At 2.3 GHz a quasi-periodic behaviour with a period of 57 days was discovered which is reminiscent to, though longer than, those found in some compact extragalactic radio sources.

1. Introduction

Sgr A* is believed to be the radio source associated with the $2.6 \cdot 10^6 M_\odot$ (Haller et al. 1996; Ghez et al. 1998 & 1999; Eckart & Genzel 1996; Genzel & Eckart 1999; Zhao & Goss 1999) dark mass concentration in the center of the Galaxy. Since we know very little about this source from other wavelengths, where it is extremely faint (see Falcke 1996 for a review), a detailed study of its radio properties is an important prerequisite for its interpretation. The overall shape of the Sgr A* radio spectrum has been discussed in many papers (e.g., Serabyn et al. 1997; Falcke et al. 1998) and the variability has been investigated by Zhao et al. (1989 & 1992). The spectral index ($S_\nu \propto \nu^\alpha$) of the source tends to be in the range $\alpha \simeq 0.2 - 0.3$ with an increasing value of α at mm-wavelength and a possible cut-off at lower frequencies. At high frequencies the spectrum cuts off in the infrared. A major problem with the investigation of its radio variability is that Sgr A* is at relatively low elevation for most interferometers, that it is embedded in a large confusing structure, and that it becomes scatter-broadened at low frequencies. The confusion especially is a major problem for single-baseline interferometers with short baselines like the Green Bank Interferometer (GBI) that is often used for variability studies. For this reason the exact nature of the variability of Sgr A* has remained inconclusive. Flux density variations are clearly seen between different epochs, but the timescale of the variability at various frequencies is not well determined and it is not clear whether some of the more extreme claims of variability are real or instrumental artifacts. So far, Zhao et al. (1989,1992) probably have presented the largest database of Sgr A* flux-density measurements. They found a number of outbursts at higher frequencies and tentatively concluded that the small-amplitude variability at longer wavelengths is caused by scattering effects in the ISM while the variability at higher frequencies is intrinsic. In this paper new results of a continuous monitoring program of Sgr A* at cm-wavelengths performed with the GBI are presented and evaluated.

2. GBI Observations and Data Reduction

Sgr A* has been part of the NASA/NRAO Green Bank Interferometer (GBI) monitoring program for the past two years. The GBI is a two-element interferometer (26m dishes) with a separation of 2400 meters, operating simultaneously at X- and S-band (8.3 & 2.3 GHz) with 35 MHz bandwidth. The resolution of the pencil beam is 3 and 11 arcseconds and 1 σ noise levels are typically 30 and 6 mJy at X and S-band respectively. The data are publically available but need further processing, since the baseline gains depend on hourangle. In addition observations of Sgr A* will also suffer from severe confusion due to the small baseline and the extended structure of Sgr A West as mentioned in the introduction.

The data were post-processed in the following way: an hourangle dependent gain correction was fitted to 1622-297 which serves as a calibrator to Sgr A*. Absolute gains were obtained using 3C286 as the primary flux density calibrator. This gain corrections were then applied to all sources and outliers were clipped when flux density measurements deviated by more than 3 σ from the median flux density within a 20 day interval. For some calculations the data were further averaged and gridded in three-day intervals. Only data after July 1997 were considered due to initial calibration problems with the GBI. All subsequent observations were made at almost the same hour angle.

Sgr A* was also corrected for confusion. Comparison of the GBI data with contemporaneous observations of Sgr A* at 5 and 8 GHz with the VLA and VLBA (Bower et al. 1999a; Lo et al. 1998; Goss 1998, p.c.) were used to calculate the difference between the GBI-single baseline flux density and the total flux density of Sgr A*, where the 2.3 GHz total flux density was obtained by extrapolation. Thus for an hourangle of ~ 0.88 hrs a flux of 70 and 177 mJy was added to the X and S-band data respectively.

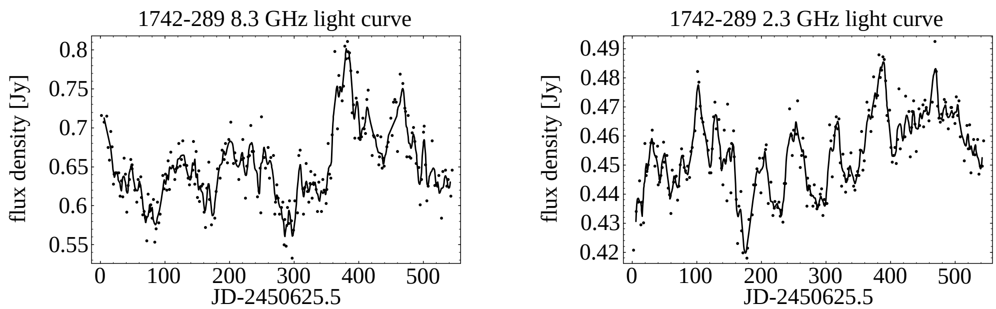

Figure 1. Radio light curves of Sgr A* at 8.3 GHz (left panel) and 2.3 GHz (right panel) measured with the GBI (dots). The solid line is the interpolated light curve for three-day averages.

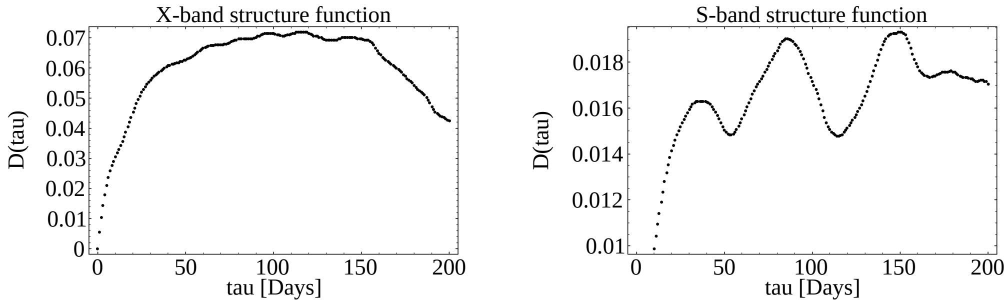

Figure 2. Structure function of the radio light curves of Sgr A* at 8.3 GHz (left panel) and 2.3 GHz (right panel). Maxima indicate a characteristic times scale, minima indicate a characteristic period

The final light curves are shown in Figure 1. One can see a peak-to-peak variability of 250 mJy and 60 mJy with an RMS of 6% and 2.5% at 8.3 & 2.3 GHz, respectively (i.e., modulation index). The median spectral index between the two frequencies for the whole period is $\alpha = 0.27$ ($S_\nu \propto \nu^\alpha$), varying between 0.2 and 0.4. There is a trend for the spectral index to become larger when the flux density in both bands increases.

3. Results

To characterize the variability pattern better, Fig. 2 shows the structure function $D(\tau)$ of the two lightcurves, where

$$D(\tau) = \sqrt{\left\langle \left(S_\nu(t) - S_\nu(t \pm \tau)\right)^2 \right\rangle} \quad . \tag{1}$$

A maximum in the structure function indicates a characteristic timescale, a minimum indicates a characteristic period. A characteristic period in radio-lightcurves usually does not persist for a long time, and hence, similar to X-ray astronomy, is commonly called a quasi-periodicity, even though the underlying physical processes are probably very different from those seen in X-ray binaries.

Interestingly, the structure functions at both frequencies look very differently. While at both frequencies the characteristic time scale is somewhere between 50 and 200 days, we find a clear signature of quasi-periodic variability at 2.3 GHz, which is not obvious at 8.3 GHz. All the three maxima and the two minima in the structure function are consistent with a period of 57 days.

A cross correlation of the two light curves gives a strong peak near zero time-lag which indicates a certain degree of correlation between the emission at 8.5 GHz and 2.3 GHz (Fig. 3). A slight offset of the peak by 2-3 days is visible (Fig. 3, right panel). Usually such an offset would indicate that the 8.5 GHz light curve precedes the one at 2.3 GHz. This would be qualitatively expected by a model where outbursts travel outwards, from high to low frequencies as for example in a jet model (Falcke et al. 1993), however, the time lag one obtains is also close to the sampling rate and it is not clear how significant this offset really

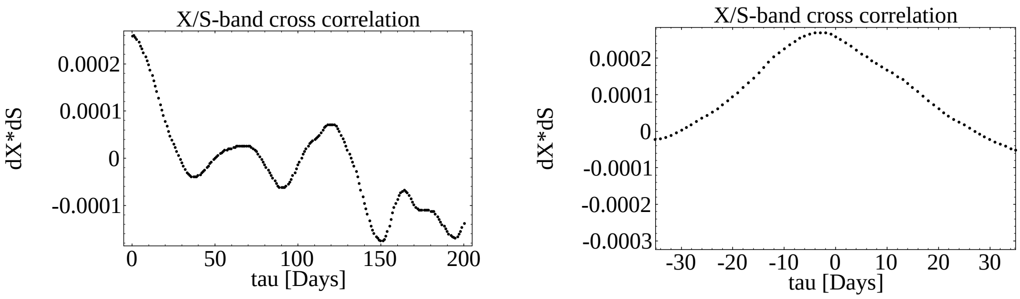

Figure 3. Cross correlation of 8.3 GHz and 2.3 GHz radio light curves of Sgr A*. In the left panel positive and negative time lags have been co-added. The right panel shows a blow-up of the cross correlation (without co-adding positive and negative lags) around zero lag.

is. Another noteworthy feature of the cross correlation is that the 2.3 GHz quasi-periodicity can still be seen. This could indicate that the quasi-periodicity is also present at 8.3 GHz, but is swamped by another, more erratic type of variability.

4. Discussion and Summary

To summarize the results one can say that there is clear evidence for variability of a few percent at cm wavelengths in Sgr A*. The variability does not seem to be consistent with a simple model of refractive interstellar scintillation (RISS) as suggested by Zhao et al. (1989&1992). The timescales at 2.3 GHz and 8.3 GHz both seem to be comparable to the one found at 5 GHz by Zhao et al. (1989&1992) and does not follow a $t \propto \lambda^2$ law. Moreover, the modulation index apparently decreases towards lower frequencies.

The quasi-periodicity is reminiscent to those in some quasar cores. For example the QSO 0917+624 is know to show episodes of quasi-periodicity (Kraus et al. 1999). Unfortunately the frequency of these quasi-periodicities in quasar cores and perhaps also Sgr A*, may not be related to a well defined and constant (e.g., precession) frequency like the QPOs in x-ray binaries, but could simply be due to intermittent periodic phenomena in the accretion disk (e.g., waves) or the jet (e.g., helical motion). In the case of Sgr A* all characteristic timescales associated with a black hole or a relativistic outflow at these frequencies are less than a day and hence one might consider global accretion flow instabilities for such a behaviour. On the other hand the possibility whether the quasi-periodicity could be produced by interstellar scattering needs to be explored as well.

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